Suspended-core fiber Sagnac combined dual-random mirror Raman fiber laser

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Abstract: In the present work, a multiwavelength fiber laser based in the combination of a double-random mirror and a suspended-core Sagnac interferometer is presented. The double-random mirror acts by itself as a random laser, presenting a 30dB SNR, as result of multiple Rayleigh scattering events produced in the dispersion compensating fibers by the Raman amplification. The suspended-core fiber Sagnac interferometer provides the multi peak channeled spectrum, which can be tuned by changing the length of the fiber. The result of this combination is a stable multiwavelength peak laser with a minimum of ~25dB SNR, which is highly sensitive to polarization induced variations.

OCIS codes: (060.3510) Lasers, fiber; (060.5295) Photonic crystal fibers; (140.3550) Lasers, Raman; (290.5870) Scattering, Rayleigh.

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1. Introduction

Since the first fiber laser was demonstrated in the 60s, a large deal of attention has been paid to potential applications. Application fields such as material processing, spectroscopy, medicine and telecommunications made this kind of lasers very attractive and popular. Basic laser schematic generally entails a gain medium that provides amplification and an optical cavity that traps the light, creating a positive feedback. Lasing occurs when the total gain in the cavity is larger than the total losses. Normally, the cavity determines the directionality of the output and its frequency. Nevertheless, there is a kind of laser whose output spectrum characteristics are mainly defined by multiple scattering and not only by the laser cavity: random lasers. Random fiber lasers present open cavities and are said to be ‘mirror-less’ or based in random mirrors since their principle of operation is based in multiple scattering events. The multiple scattering of photons in an amplifying medium increases the effective optical path, thus enhancing laser amplification [1–3].

Several multiwavelength fiber lasers have been demonstrated using a random mirror in combination with another reflector mirror, normally used as the wavelength selector. Multiwavelength fiber lasers taking advantage of fiber Bragg gratings (FBGs) in combination with a random mirror have been demonstrated: in a 200 km long Raman fiber laser using two different wavelength FBGs with a random mirror [4]; or in a Raman fiber laser based on multiple point-action FBG reflectors and distributed feedback via Rayleigh scattering in an ~22 km long optical fiber [5]. Another frequently used wavelength filter employed in combination with random mirrors is the Sagnac loop. It can be applied in combination with another mirror (physical or random) or by simply inserting it in the middle of the structure to modulate the output spectrum. Sagnac interferometers based in photonic crystal fibers (PCFs) stand out due to their low thermal sensitivity, low insertion loss and polarization independence to input light [6,7]. These advantages make them especially suitable as multi-peak selectors, leading to improved stability in multiwavelength fiber lasers [8]. Recently, a multiwavelength Raman fiber laser was demonstrated using the combination of a PCF based Sagnac structure with a random mirror [9]. This Raman fiber laser presented a simple structure based in a random mirror combined with a reflective mirror. The dispersion compensating fiber (DCF) acts as the gain medium while acting as a random mirror, due to the multiple Rayleigh events occurring in this fiber do to Raman gain; whereas the PCF based Sagnac acts as a reflective mirror while providing the interferometric spectrum. Other structures developed based in the combination of a random mirror with a reflective mirror are fiber laser sensors. In this kind of structure, the reflective mirror acts as a sensing element while being one of the mirrors of the laser. A fiber laser sensor for strain and temperature measurement was already developed based in the combination of a random mirror with FBGs [10]; and more recently, a suspended-core Fabry-Perot cavity was used in combination with a random mirror in order to obtain a simple laser sensor configuration for temperature sensing [11].

In the last year, the demonstration of a laser based only in multiple scattering, without any additional reflectors, was a breakthrough in this area of research. A stable continuous wave lasing in 83km single mode telecommunications fiber using only Raman amplification and Rayleigh distributed feedback was accomplished [12]. The use of long length of standard single mode fiber and the complete absence of end mirrors makes this laser very different

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from any previous demonstrated laser, being the only resonant element the Raman amplification line provided by the pumped optical fiber.

In this paper, a Raman fiber laser composed by double-random mirrors using a suspended-core fiber Sagnac interferometer as the channel filter is proposed. The double-random mirrors act as a broadband laser, as a result of the multiple Rayleigh scattering signals produced in the dispersion compensating fibers by the Raman amplification. The suspended-core fiber Sagnac loop provides the interferometric signal, which can be tuned by changing the length of the fiber. The fiber laser multi-peaks can be tuned by the length of the suspended-core fiber and by changing the polarization state in the Sagnac interferometer.

2. Experimental configuration

The proposed Raman fiber laser is based on the structural set up presented in Fig. 1. The set up consists in a Raman laser pumping at 1445 nm (maximum power of 3.3W), an isolator (ISO), a 48:52 optical coupler (OC) with low insertion loss, two wavelength division multiplexers (WDMs), two dispersion compensating fibers sections and a fiber Sagnac structure. An optical spectrum analyzer (OSA), with a maximum resolution of 10 pm, was used to observe the laser output spectra. Each of the dispersion compensation fibers presents a dispersion of −343 *ps/nm/km* at 1545 *nm*, an insertion loss of ~3.4*dB* and a length of 2.4km. These 2.4km of DCF represent nearly a compensation length of 20km of standard SMF, due to its lower effective area and higher dopant concentration. The Sagnac structure is formed by a 3 dB optical coupler with low insertion loss, ~50cm suspended-core fiber, and an optical polarization controller (PC) for optimized adjustment of the output spectrum.

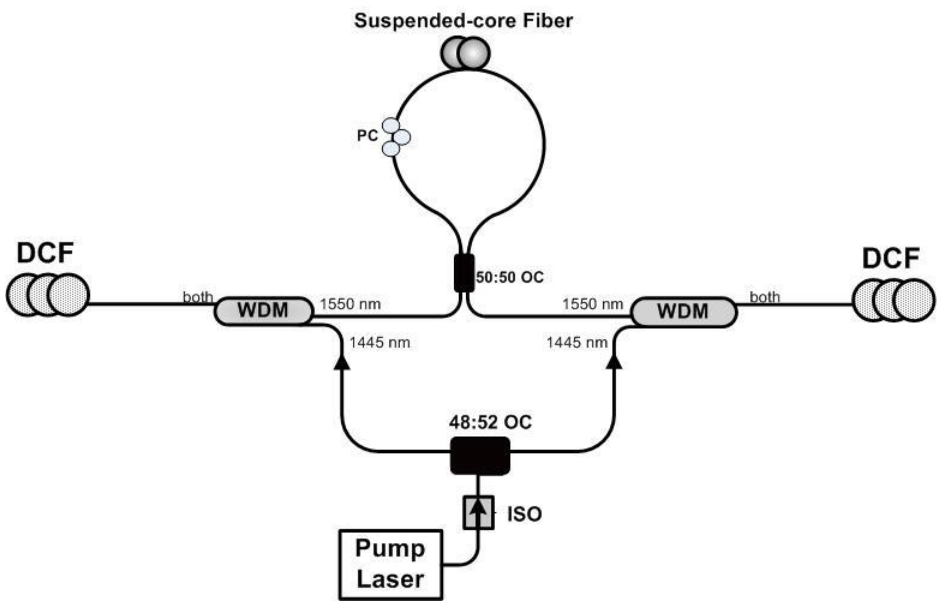

Fig. 1. Experimental set up for the proposed Raman fiber laser.

The suspended-core fiber was fabricated at the IPHT (Institute of Photonic Technology, Jena, Germany) and is formed by three holes with a diameter of 45 μm (inset Fig. 1). The core and the cladding have diameters of 6 μm and 127 μm, respectively. The core, as well as the fiber, have a slightly triangular shape due to the hole asymmetry originated during the fabrication process. The total loss of both splices was measured to be ~3dB.

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3. Principle of operation

The proposed Raman fiber laser results of a suspended-core Sagnac filter modeling a double-random mirror laser. The double-random mirror acts as a broadband fiber laser, whereas the suspended-core Sagnac loop acts as a tuning element of the output spectrum, due to the asymmetry induced in the pump powers reaching the DCFs which leads to different random mirrors. The principle of operation of the components of the laser is shown below.

3.1 Double-random mirror laser

The double-random mirror laser is formed by two random mirrors, each of them induced by the Raman gain in each DCF. A random mirror is the direct consequence of Raman pumping in the fiber. When there is Raman gain in the fiber, Rayleigh scattering is created in the counter-propagating direction of the signal. This Rayleigh scattering signal can undergo another scattering event, due to the Raman gain. This second scattering event, called double Rayleigh scattering, will co-propagate with the signal and pass through the amplifier experiencing gain. These events will occur all through the fiber and, therefore, there will be time-delayed replicas of many signals, leading to superpose signals and, as a result, noise. This Rayleigh associated noise can become a major source of power penalty in Raman amplified lightwave systems. As the gain in the Raman amplifier increases, so will the Rayleigh associated noise, which will eventually limit the achievable gain of the Raman amplifier [13]. Nevertheless this multiple Rayleigh events can be used as part of the lasing system, transforming this Rayleigh associated noise in part of a ‘mirror’ in the laser cavity.

By using the configuration presented in Fig. 1 without the Sagnac interferometer a laser is obtained. Each of the DCFs acts as a random mirror, which leads to a stable broadband laser in the lasing span defined by the fibers Raman gain. Figure 2 presents the spectral response of the double-random Raman fiber laser for a pump power of 1.4W.

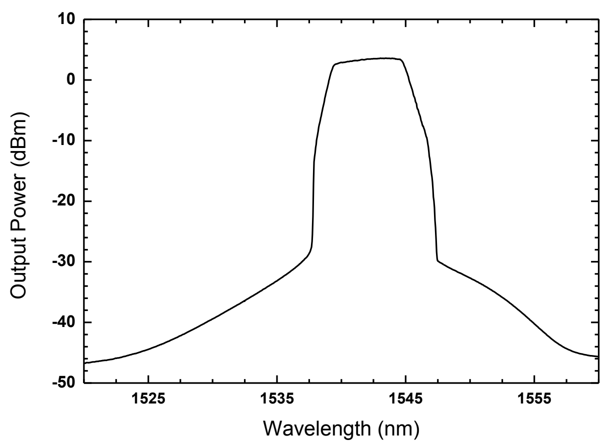

Fig. 2. Double-random mirror induced laser output signal for a pump power of 1.4W.

A lasing range of ~10nm was obtained with a broadband shape spectrum and a signal-to-noise ratio (SNR) of ~30dB. Closely observing the output spectrum in Fig. 2, a little asymmetry in the shape of the spectrum can be noticed. The spectrum presents a little slope. This asymmetry is introduced by the 48:52 OC, which ensures 4% more of pump power to one of the DCFs, introducing a little difference between the random mirrors forming the fiber laser. The random lasing is achieved simply throughout multiple Rayleigh scattering and Raman amplification induced in both DCFs, with a difference in strength. This random fiber laser is based on the same effect as the one presented in reference [12], despite of the fact that it uses approximately half the fiber length and only one pump wave.

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3.2 Suspended-core fiber Sagnac interferometer

The suspended-core fiber Sagnac interferometer is formed by an optical coupler spliced to a suspended-core fiber and a polarization controller. The optical coupler splits the input signal equally into two counter propagating waves. These waves travel trough the optical path with different velocities, due to the birefringence of the fiber. After propagating around the loop, these waves will recombine at the coupler. The difference in the propagating wave's velocities will lead to a variable interference term in the output port. The different propagation velocity of the waves in the Sagnac loop is due to the birefringence ($\beta = n_y - n_x$) of the fiber, which is a physical parameter that relates the difference in refractive indices of the propagation's axis. This birefringence will lead to a transmission output which is approximately a periodic function of the wavelength:

$$T = \left[\sin\frac{\beta L}{\lambda}\cos\left(\theta_1 + \theta_2\right)\right]^2 \tag{1}$$

Where L is the length of the fiber, λ the wavelength of operation and θ_1 and θ_2 are the angles between light in the propagation axis at the end of the suspended-core fiber. The wavelength spacing ($\Delta\lambda$) between two consecutive interference channels in the transmission spectrum is given by:

$$\Delta\lambda = \frac{\lambda^2}{\beta L} \tag{2}$$

From Eq. (2), it can be seen that the wavelength spacing between two consecutive channels in a Sagnac loop is inversely proportional to the birefringence and length of the fiber (in this case, ~50cm of suspended-core fiber). Its spectral characteristics are only dependent on these two parameters and, as so are independent of the polarization state of the input light [14]. Figure 3 presents the experimental transmission spectra for the Sagnac interferometer used as the selective wavelength filter in the fiber laser, presenting 8 peaks in a span of 5nm with ~0.625nm spacing between two consecutive peaks.

One of the advantages of using this interferometer as the wavelength selecting unit is the ability to easily tune the output spectrum. By simply changing the length (see Eq. (2)) of the suspended-core fiber, one can modify the wavelength spacing between consecutive peaks and consequently the number of lasing channels in a given span. Another great advantage of this filter is its insensitivity to environmental changes. Since the two interfering waves counter propagate in the same fiber and are exposed to the same environment, the Sagnac interferometer is almost insensitive to environmental noise.

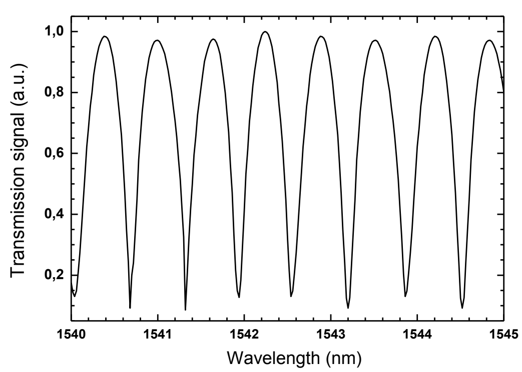

Fig. 3. Transmission signal of the Sagnac interferometer used in the fiber laser.

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4. Results and discussion

A multiwavelength fiber laser is achieved by using the asymmetry induced in the pump powers reaching each of the DCFs, which by consequence will influence the intensity of the random mirrors, which in turn leads to an asymmetry between the multiple Rayleigh backscattered signals arriving to the Sagnac interferometer from each of the DCFs.

By combining the double-random mirror induced laser with the Sagnac wavelength selector a multiwavelength fiber laser is obtained. Figure 4 presents the output spectrum of the fiber laser configuration, presented in Fig. 1, for a pump power of 1.4W after optimized adjustment of the polarization control. The output spectrum of the proposed laser presents 7 lasing channels in a 5nm span, with ~0.71nm spacing between two consecutive peaks and a minimum ~25dB SNR.

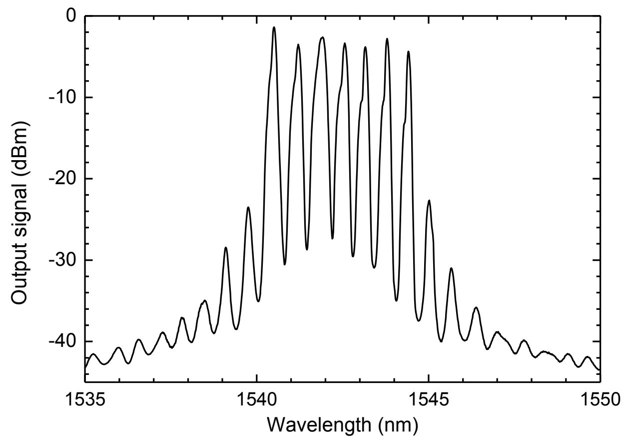

Fig. 4. Output spectrum of the proposed fiber laser for a pump power of 1.4W.

The channel spacing of the laser output spectrum is higher than the one of the Sagnac interferometer alone, leading to a lower number of channels in the same span. This is due to the fact that the Sagnac interferometer is in the middle of the laser cavity, being illuminated from both ports. The wavelength spacing, and consequently, the number of lasing channels are tuned by the Raman gain and the length of the suspended-core fiber in the Sagnac loop. The Raman gain and multiple Rayleigh scattering events are the only added part from Fig. 3; as so, the difference in the wavelength spacing due to the multiple Rayleigh scattering events running in both directions in the Sagnac interferometer, which leads to a slightly broadening of the peaks [15].

Instabilities due to stimulated Brillouin scattering (SBS) were considered suppressed in this work. Stimulated Brillouin transfers energy from a high-frequency channel to a low-frequency channel when the channel spacing equals the Brillouin shift. When lasing starts SBS and other non-linear effects can contribute to the generation of the output spectrum of the laser. But for lasers with linewidths $\Delta\nu_L$ larger than 20 MHz SBS gain decreases as the ratio $\Delta\nu_B/\Delta\nu_L$, that is, $g = g_B\Delta\nu_B/\Delta\nu_L$, where g_B is the maximum steady state Brillouin gain [16]. As a consequence, it can be reasoned that Raman amplification leads the behavior of this laser and the Brillouin effect is suppressed.

Since this laser's wavelength cavity selector is a Sagnac interferometer, the multiwavelength output spectrum will be highly sensible to polarization induced alterations. By changing the polarization, distinct output spectra can be found. Figure 5 presents some of the output spectra that can be obtained changing the polarization controller parameters.

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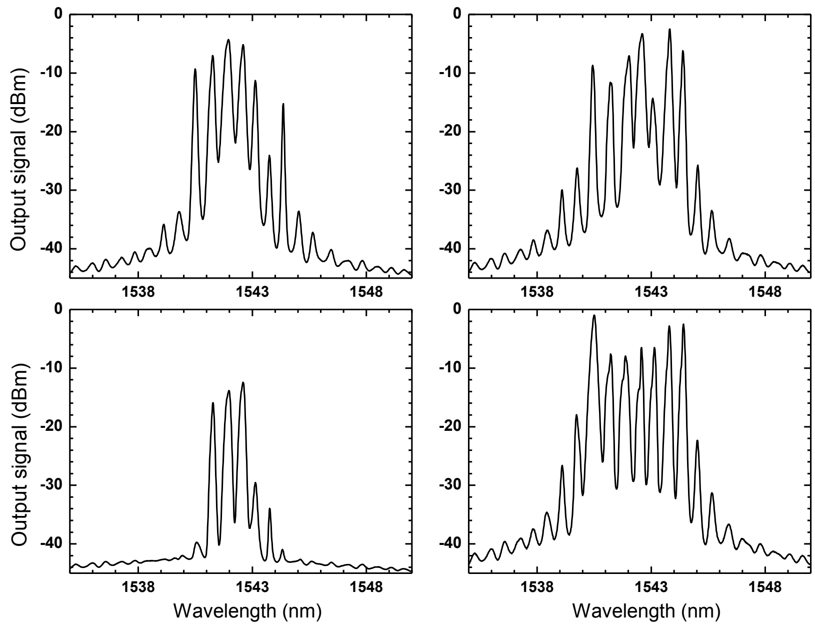

Fig. 5. Polarization dependence of the output spectrum of the proposed fiber laser, for a pump power of 1.4W.

The shape, SNR and number of lasing channels of the spectrum can be tailored by the polarization controller. Consequently, the laser output spectrum can be easily modified by the polarization controller in order to obtain the desired spectrum for a given application.

The multiwavelength fiber laser presents a characteristic output behavior when pumped by higher powers, as it can be seen in Fig. 6. With increasing pump power the output power maximum shifts to longer wavelengths, due to the effect of cascaded Raman scattering. The same was already observed by other authors [5], were the laser's distribution became flatter but less uniform.

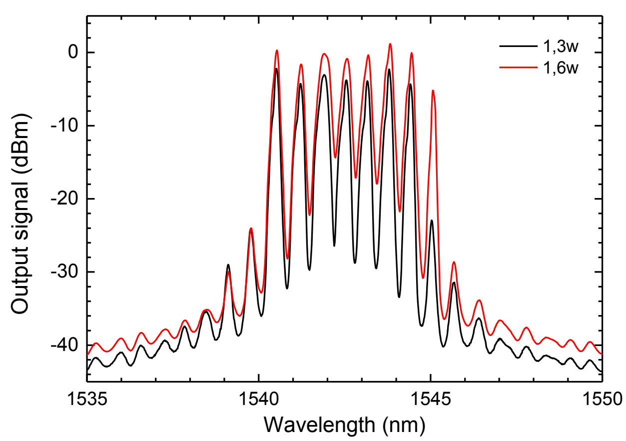

Fig. 6. Output spectrum of the proposed fiber laser for two different pump powers.

By measuring the laser's output power for each pump power a linear relationship was founded. The obtained data is presented in Fig. 7. For small pump powers, below the threshold pump power (1W), an exponential growth was found. When reaching the threshold

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and passing it, a linear relationship was observed, as should be expected since in Raman amplification the output power is directly proportional to the pump power.

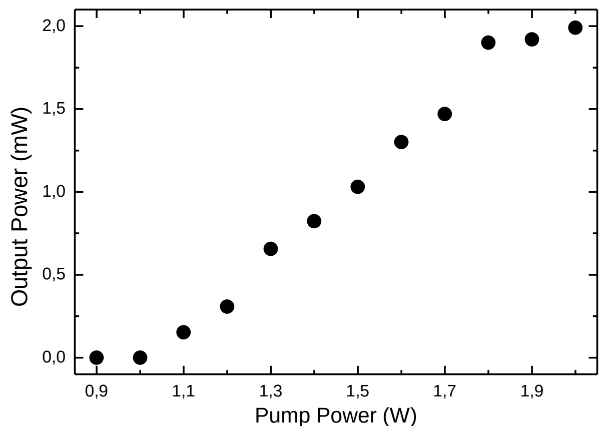

Fig. 7. Fiber laser's output power vs pump power.

In order to determine the stability of the fiber laser presented, the power fluctuations of the laser were measured during one hour, in time intervals of 2 minutes. Figure 8 presents the optical power fluctuations of one peak line. As it can be observed, in a time window of one hour the fiber laser presents a maximum power variation of ~0.5dB, which is a much lower value than the ones presented in stability studies of typical configurations using Raman amplification [17].

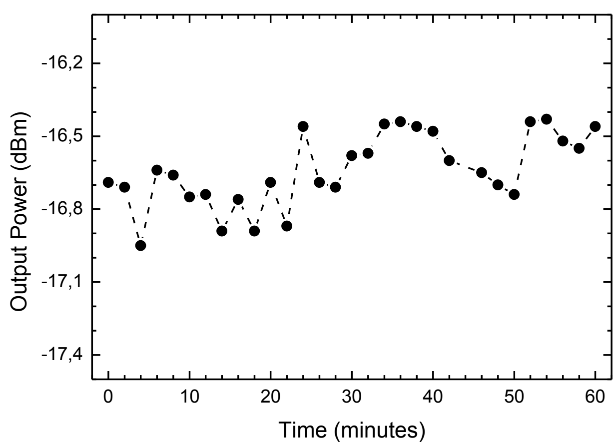

Fig. 8. Fiber laser's isolated peak power fluctuations.

4.1 Sensing applications and future work

The proposed multiwavelength Raman fiber laser presents suitable characteristics for applications such as sensing illumination system or sensors interrogation. By using this fiber laser as the illumination source for FBGs, for example, the interrogation of temperature or displacement can be done using the interrogation technique presented in [18]. However, when using the presented multiwavelength fiber laser as the illumination source, the FBGs act as the sensible heads. Moreover, by replacing one of the DCFs with 50km of SMF fiber (already experimentally obtained by the authors) remote sensing can be obtained. Future work involves reaching longer fiber lengths for application in long remote sensing systems.

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Furthermore, the proposed configuration can be used as laser sensor by simply exploiting the sensing skills of the Sagnac configuration. The presented lasing structure was tested for temperature changes and displacement variations. By subjecting the suspended-core fiber in the Sagnac structure to temperature and displacement variations insensibility to temperature changes was observed as well as sensitivity to displacement variations.

The displacement measurements were based in bending. Bending was performed in the suspended-core fiber with the bending plates showed in Fig. 9.

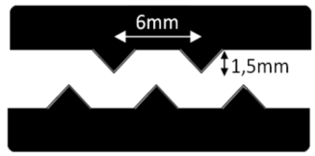

Fig. 9. Schematics sketch of the bending plates used for displacement testing in the multiwavelength fiber laser.

The suspended-core fiber presents high confinement of light in the core as a consequence of the elevated refractive index difference between the core and the three air holes cladding. Due to this elevated confinement there are no cladding-mode coupling problems, avoiding this way the unwanted cladding re-coupling modes. The bending plates change the birefringence of the fiber and thus the polarization state of the transmitted light in a controlled way, from an interference maximum to an interference minimum. Preliminary experiments were preformed in a short (230μm) displacement range using 1.7μm steps, and the results are showed in Fig. 10. The dots in the graph represent experimental results and the dashed line, the linear regression. A sensitivity of ~0.011 dB/μm and stability of ~0.5dB in one hour were obtained. Experiments for improving the sensitivity and enlarging the displacement range are in progress due to these promising results.

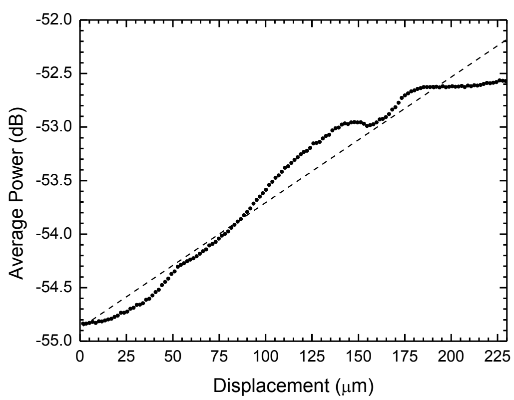

Fig. 10. Fiber laser's preliminary results for the output power variations with displacement. The dots represent the experimental results and dashed line the linear regression.

5. Conclusions

An original configuration for a multiwavelength Raman fiber laser was proposed and demonstrated. The multiwavelength fiber laser is composed by a double-random mirror induced laser using a suspended-core fiber Sagnac interferometer as the channel filter. The double-random mirror acts by itself as a broadband laser with a 30dB SNR, being the result of multiple Rayleigh scattering produced in the dispersion compensating fibers by the Raman amplification. The suspended-core fiber Sagnac loop provides the interferometric signal, with the help of an asymmetry introduced in the pumping scheme of the fiber laser. The multi peak

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distance and number can be tuned by simply changing the length of the fiber. The multiwavelength fiber laser's output has a multi-peak spectrum presenting 7 lasing channels with a minimum of ~25dB SNR. The wavelength spacing between lasing channels and the number of lasing channels can be easily tuned by the length of the suspended-core fiber. In addition, the fiber laser's output is highly sensitive to polarization induced changes in the Sagnac filter. As such, by tailoring the polarization controller condition different shapes, SNR and number of lasing channels can be obtained. The proposed multiwavelength Raman fiber laser presents suitable characteristics for applications such as sensing illumination system or sensors interrogation. Even more, the proposed configuration can be used as laser sensor by simply exploiting the sensing skills of the Sagnac configuration.

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